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Review Paper

Location matters. A systematic review of spatial contextual factors mediating ecosystem services of urban trees

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ABSTRACT

To ensure and maintain ecosystem service delivery in cities undergoing densification, strategic tree planting is important. The effects of tree location on ecosystem service delivery have been emphasised. However, there is no integrated overview of the different aspects of tree location, here called spatial contextual factors, that mediate urban tree ecosystem services. This paper presents the results of a systematic literature review and provides a comprehensive overview of spatial contextual factors recognised by research as relevant for ecosystem service delivery by urban trees. To support creating such an overview, we first gain insight into the current common understanding of what spatial context is conceptually and how it participates in the co-production of ecosystem services. We find that generally, spatial context is represented by both social and ecological structures and processes and that it mediates ecosystem services by four mechanisms along the ecosystem service cascade. In the next step, we identify 114 unique spatial contextual factors mediating 31 ecosystem services of urban trees. Of all factors, people, represented by physical location, socio-demographics or building functions, mediate the highest number of services, highlighting the importance of urban planning and design in mediating urban tree ecosystem services.

1. Introduction

1.1. Background

Rapid urban growth accompanied by climate change is associated with problems such as air and noise pollution, urban heat island effect, increased stress levels, habitat loss and flash floods (Ahlfeldt and Pietrostefani, 2017; Bazaz et al., 2018; Berghauser Pont et al., 2020; Gren et al., 2018). Research suggests that urban trees, i.e. trees in both public and private areas (parks, streets, urban forest and gardens respectively), have the potential to contribute to mitigating these problems and contributing to the well-being of urban citizens by delivering a range of benefits. These benefits that nature can provide to humans have been conceptualized by the framework of ecosystem services (ES) (Daily, 1997; De Groot et al., 2002; Millennium Ecosystem Assessment, 2003; TEEB, 2010). Urban trees deliver provisioning, regulating, cultural and supporting ecosystem services (Escobedo et al., 2011; Salmond et al., 2016; Säumel et al., 2016) with a variety of economic, social and health benefits (Roy et al., 2012). In addition, urban trees might also lead to nuisances, harms and costs, collectively referred to as ecosystem disservices (Lyytimäki, 2017; von Döhren and Haase, 2015).

At the same time, urbanization puts pressure on green spaces in and around cities and in consequence influences the ES they deliver (European Environment Agency, 2006; Haaland and van den Bosch, 2015). Land-use competition caused by densification and compact city development leads to urban green space losses and fragmentation within cities, but at the same time can safeguard open space outside cities (Gren et al., 2018). While the latter can be supportive for biodiversity, the loss of green areas within cities negatively impacts living quality, recreation opportunities and biodiversity (Haaland and van den Bosch, 2015).

Urban trees demand relatively little ground surface space while making effective use of vertical space to provide vegetative surface and can therefore be easier integrated in cities than larger green areas, even in high-density neighbourhoods. Tree planting and tree management are therefore vital to ensure, maintain and support the delivery of ES and associated benefits in cities where space by definition is scarce (Haaland and van den Bosch, 2015; Vogt et al., 2017). In this paper, we therefore use the individual tree as our study object (i.e. service providing unit

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(Andersson et al., 2015)).

The amount of ES delivered by individual urban trees varies depending on characteristics of the tree itself and contextual factors[1], which should be accounted for in tree planting strategies and tree management aiming to support the benefits obtained from trees (Davies et al., 2017; Roeland et al., 2019; Roy et al., 2012; Salmond et al., 2016). An example of tree characteristic is stem diameter, which, by influencing tree dry-weight biomass and growth rates, determines for instance the rate of carbon sequestration, an important ES (Nowak et al., 2002; Nowak and Crane, 2002). An example of a contextual factor is the position of the tree towards other trees and structures, which, together with a range of other contextual factors such as local growing conditions or length of growing season, determines how much carbon a tree really will sequester (Nowak et al., 2008; Nowak and Crane, 2002). Unlike tree characteristics, contextual factors co-determine the delivery of ES through their interaction with the tree (Andersson et al., 2015; Palomo et al., 2016; Spangenberg et al., 2014). The importance of contextual factors in ES delivery in general has been discussed on a theoretical and practical level (e.g. Andersson et al., 2015; Luederitz et al., 2015; Bruckmeier, 2016; Wilkerson et al., 2018). Specifically, it extends the scope for variables to be considered in ecosystem accounting and environmental benefit transfer (Luederitz et al., 2015; Keith et al., 2019).

The common denominator of contextual factors, as defined for this paper, is that they can be associated with a geographic location and their relationship to the tree can be described and measured in a spatially explicit manner. For instance, in the previous example of carbon sequestration, the contextual factor "length of growing season" varies with geographical location and the contextual factor "position of a tree towards other trees or structures" can be described in terms of their co-location in space which leads to crown competition. Therefore, we adapt the term "contextual factor" (Andersson et al., 2015; Reyers et al., 2013) and add a prefix "spatial" to emphasize the role of space.

There are various ways in which spatial contextual factors mediate or co-produce the delivery of ES by urban trees. Looking again at the example of carbon sequestration, a change in growing conditions or crown competition will lead to a change in the supply of the service, while ongoing climate changes might influence the demand for or appreciation of the service, as reflected for instance in an increase of the social cost of carbon (Nordhaus, 2017). Thus, spatial contextual factors can mediate various aspects of the ES delivery process – both its supply and demand (Burkhard et al., 2012). A helpful conceptualization of the ES delivery process in this regard is the ES cascade framework (Haines-Young and Potschin, 2010). In this framework[2], the ES delivery process is decomposed into a linked set of five key components, which span both the supply and demand aspect of the ES delivery process (i.e. biophysical structure, function, service, benefit, value). To highlight how spatial contextual factors participate in the co-production of each of these five components, Fedele et al. (2017) further adjusted the cascade by making explicit the four mediating mechanisms (i.e. management, mobilization, allocation-appropriation, appreciation), which lead from one component of the cascade to the next.

1.2. Identified gaps and paper objectives

From the above, we can conclude that spatial context is an important aspect in the ES delivery process, necessary to better understand, assess and measure ES delivery. However, to our best knowledge, a comprehensive overview of spatial contextual factors for urban trees is not available. Papers presenting reviews of factors mediating ES of urban trees do not explicitly discuss the role of tree location and the spatial relationship between trees and surrounding structures and processes in delivering ES (Davies et al., 2017; Keeler et al., 2019). Furthermore, they often focus only on a single ES such as air quality or microclimate regulation (Abhijith et al., 2017; Salmond et al., 2016) or specific factors such as institutional barriers (Biernacka and Kronenberg, 2018) or do not link tree location characteristics to individual ES (Vogt et al., 2017).

The *main objective* of this paper is therefore to develop such comprehensive overview of spatial contextual factors using a systematic literature review guided by the following two research questions: (i) What are the spatial contextual factors participating in the delivery of ES by urban trees and (ii) By what mechanisms do these spatial contextual factors mediate the delivery of ES by urban trees? However, in scientific literature on ES assessment, there is no common conceptual understanding of what spatial context is or which kinds of structures and processes represent spatial context. This hinders the immediate development of such an overview. Furthermore, the mechanisms by which spatial context mediates ES delivery seem not to be agreed upon. For example, Andersson et al. (2015) explore socio-technological, ecological and cultural contexts and how these affect the transfer from ecological functions to services. Wilkerson et al. (2018), for instance, investigate the influence of context on the supply, demand and benefits of urban ES – but focus on socio-economical context only.

Therefore, a *sub-objective* of this paper necessary to reach its main objective is to gain insight into the current common understanding of what spatial context is conceptually, i.e. what structures and processes represent spatial context, and how it participates in the co-production of ES, i.e., what are the mechanisms (Fedele et al., 2017) by which these spatial contextual factors mediate ES delivery.

2. Methods

2.1. Workflow

The method consisted of two systematic literature reviews[3] (Review 1 and Review 2), where the second literature review addressed the main objective of the study and the first literature review addressed the sub-objective of the study. The knowledge established in Review 1 was used to organise and synthesize the findings of Review 2, resulting in an overview of spatial contextual factors currently recognised by research as mediating the delivery of ES by urban trees (Fig. 1). In this overview, individual spatial contextual factors are grouped by the structures and processes they represent and, through mediating mechanisms, linked to the ES they mediate (Results box in Fig. 1).

2.2. Literature review 1

We conducted a systematic database search (Web of Science, Google Scholar) using predefined search terms, which were formulated to find articles focusing on the role of spatial context in ES delivery. We did not use "spatial context" as a single search term because researchers might not specify the spatial component of context explicitly. On the other hand, the simpler term "context" has a too broad meaning, which was reflected in more than 3.000 hits when applying the search term *"context*" AND "ecosystem service*"*. Therefore, we used a series of more specific terms, namely *("contextual factor*" OR "context depend*" OR*

[1] Contextual factors (Andersson et al., 2015; Reyers et al., 2013) are also referred to as "mediating factors" that co-produce the delivered ES (Fedele et al., 2017), but we will use the term "contextual factors" to avoid confusion with the term "mediating mechanisms" used later in the article.

[2] The interpretation of individual components in the ES cascade and the links between them differs with the purpose of use, analysed ecosystem and scale (Heink and Jax, 2019). Acknowledging the diversity of interpretations, in this paper, we understand the individual cascade components as presented in the Supplementary Material (sheet "ES cascade").

[3] By a "systematic literature review" we understand a review following predefined review steps (definition of search terms, reading identified articles using pre-defined exclusion criteria, extracting specific information), as used for instance in Czúcz et al. (2018) or Heyman et al. (2018).

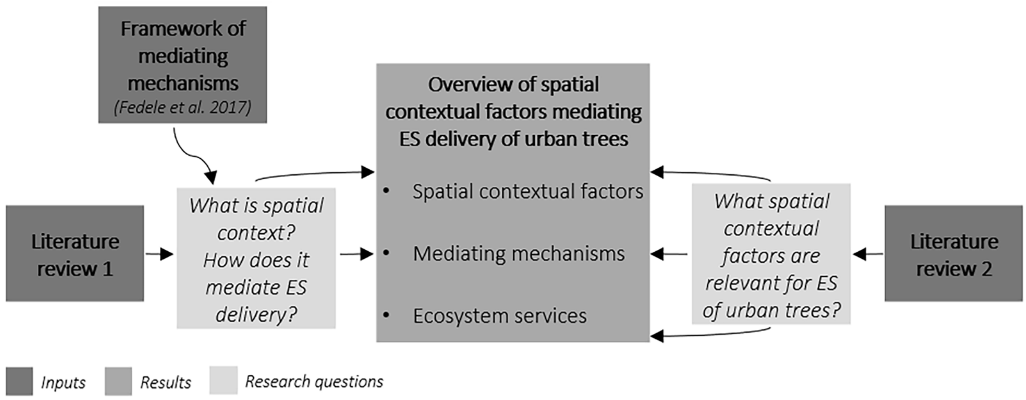

Fig. 1. Methodology workflow.

"mediating factor" OR "spatial context*") AND "ecosystem service*"*. We also used the combination *"context*" AND "cascade" AND "ecosystem service*"* to find articles relating spatial context to the ES cascade. For Web of Science, we did not restrict the timespan of the articles; for Google Scholar, we used the first 20 hits, sorted by relevance.

The database search was conducted on September 17, 2019 and revealed 159 articles from Web of Science and 20 articles from Google Scholar. We complemented the result with four articles recommended by experts in the field.

In the next step, titles and abstracts of the 183 articles were systematically screened using the following three exclusion criteria that narrowed down the selection to 27 articles:

- We excluded duplicate articles,
- We excluded articles that did not use the term "context" in direct relation to ES delivery (e.g., an article stating that "the study is carried out in the context of urban area" would be excluded), or which only vaguely emphasized the effect of spatial context in relation to ES delivery (e.g., an article stating that "considering the context in ES quantification is important" would be excluded),
- We excluded articles that study the concept of spatial context for a particular ES only, or provide concrete examples of spatial contextual factors without the possibility to generalise for all services (e.g. air pollution removal by trees is mediated by pollution concentrations, but this cannot be generalized). However, in case those articles studied urban trees, they were kept as input to Review 2.

In the following step, the full texts of the 27 articles were screened to identify the distinct notions of spatial context related to the mediation of ES delivery. In correspondence with the focus of this paper, we recorded the following information for each notion of spatial context:

- The term used to refer to spatial context,
- The structures or processes that represent spatial context,
- Description of the ways in which spatial contextual factors mediate ES delivery,
- The studied ecosystem,
- An example.

Of the 27 articles, 19 articles did not specify any concrete notion of spatial context in relation to ES delivery (see sheet "Review 1 – ref" in the Supplementary Material for a list of the individual articles). From the remaining 8 articles, we identified 57 distinct notions of spatial context in relation to ES delivery. These were recorded in a table where each row represents one notion and the columns represent the recorded information (see sheet "Review 1" in the Supplementary Material).

In the next step, these 57 notions were manually grouped based on similarities in the structures and processes that can represent spatial context. We identified five general domains of structures and processes and labelled them as *aggregation of biophysical structures*, *natural structures and processes*, *built structures and processes*, *individuals and society* and *maintenance and governance* (see sheet "Domains" in the Supplementary Material for an overview of the identified domains of structures and processes).

Based on the description of the ways in which spatial contextual factors mediate ES delivery, we then associated each notion with one of the four mediating mechanisms from the conceptual framework of mediating mechanisms developed by Fedele et al. (2017), i.e. management, mobilization, allocation-appropriation, appreciation (see sheet "Mechanisms" in the Supplementary Material for an overview of the individual mediating mechanisms). This framework was created to study how humans co-produce ES. To fit this framework to all five identified domains of structures and processes, we used the recorded descriptions of the ways in which spatial contextual factors mediate ES delivery and interpreted the original meaning of the individual mechanisms suggested by Fedele et al. (2017) to capture this wider scope.

2.3. Literature review 2

Relevant literature was primarily identified by a systematic search on the Web of Science database using predefined search terms, limited to peer-reviewed journal articles. Additional articles were identified through recommendations by experts in the field, by reference follow-up and from articles that were kept from Review 1. The following search terms were used to include all articles on trees in urban environments: *("urban tree*" OR "street tree*" OR "urban forest*" OR "green space*" OR "green infrastructure*" OR "park") AND ("urban*" OR "city" OR "cities")*. To limit the search to articles related to quantification or valuation of ES, which are likely to investigate spatial contextual factors mediating ES delivery, the following search terms were used: *("quanti*" OR "valu*")*. To further limit the search to cover literature that investigates tree benefits both with and without an explicit link to the ES framework, we included the search terms: *("ecosystem service*" OR "benefit*")*. Finally, we only included secondary sources (i.e. review articles using the search terms *"review*" OR "literature" OR "synthesi*" OR "meta-analysis"*) to more efficiently gain an overview of the spatial contextual factors used in scientific literature.

The timespan of the articles was not restricted. The database search, conducted on October 23, 2019, resulted in 320 articles in total; 50 additional relevant articles were identified through the reference follow-up, from articles that were kept from Review 1 and from recommendations by experts in the field.

In the title, abstract and full text screening, the following five exclusion criteria were used:

- We excluded articles that did not have urban areas as their primary focus,
- We excluded articles that did not specifically study individual trees or trees as components of larger green areas,
- We excluded articles reporting on original (primary) research (i.e. not being review articles),
- We excluded articles that did not quantify or value ES,
- We excluded articles that did not specify any spatial contextual factors.

Of the 370 articles, the title and abstract screening narrowed down the selection to 118 articles (see sheet "Review 2 – ref" in the Supplementary Material for a list of the individual articles). The full text screening of the 118 articles resulted in a final sample of 52 articles because 66 articles did not specify any spatial contextual factors. This final sample of 52 articles was then screened to identify spatial contextual factors. For each notion of spatial contextual factor identified, we recorded the following information:

- The term used to refer to the spatial contextual factor,
- ES mediated by the spatial contextual factor,
- Text from the paragraph or group of sentences explaining how the spatial contextual factor mediates the ES.

We extracted 861 notions of spatial contextual factors and organised them in a table where each row corresponds to one identified factor and columns correspond to the recorded information (see sheet "Review 2" in the Supplementary Material).

To enable a systematic approach towards the synthesis of the literature review, the recorded information was categorized according to the spatial contextual factor, ES and mediating mechanism.

The identified spatial contextual factors were hierarchically labelled on three levels of aggregation. On the most disaggregate first level, we listed the spatial contextual factors adapted from the individual articles, where factors with similar meaning but different names were assigned a common label. For instance, "distance to adjacent buildings" and "space between trees and buildings" were both relabelled as" distance to building". On the second level of aggregation, we grouped the spatial contextual factors based on the structure or process that is in focus, such as "building" in the case of "distance to building". Further, a distinction was made between factors that explicitly describe the spatial relationship with a tree such as "*distance* to building" or "*visibility* from building" and those where this is only implicit such as "building geometry" or "building type". Finally, on the most aggregate third level, we distinguished between the five general domains of structures and processes representing spatial context as was identified in Review 1: *aggregation of trees* (we adjusted the general name *aggregation of biophysical structures* to fit specifically urban trees), *natural structures and processes*, *built structures and processes*, *individuals and society* and *maintenance and governance*. On all three levels, label "other" was used for factors mentioned in a single article only and label "unspecified" was used for factors that did not specify any concrete description of tree location. See sheet "Factors" in the Supplementary Material for an overview of the identified spatial contextual factors and hierarchical labels and number of citing articles.

The identified ES were hierarchically labelled on two levels. The first level differentiates between the widely used categories of provisioning, regulating, cultural and supporting services (Millennium Ecosystem Assessment, 2003; TEEB, 2010) and ecosystem disservices (Lyytimäki, 2017; von Döhren and Haase, 2015); the second level differentiates between specific services/disservices such as food provisioning, air pollution removal, recreation and health or view blockage. The names of specific services/disservices were adapted from the individual articles and the final list of individual ES is comparable to those used e.g. by Escobedo et al. (2011), Roy et al. (2012), Gomez-Baggethun and Barton (2013) or Säumel et al. (2016). In most cases, it was also possible to find an equivalent ES in the Common International Classification of Ecosystem Services (CICES) (Haines-Young and Potschin, 2018). Label "unspecified" was used in case a spatial contextual factor was mentioned without a link to a particular ES. See sheet "ES" in the Supplementary Material for an overview of the identified ES.

Finally, we associated one of the four mediating mechanisms identified in Review 1 with each identified spatial contextual factor using the recorded information explaining how individual spatial contextual factors mediate ES. If the provided information in the article was unclear at this point, we recorded "unspecified" mechanism.

This strategy of hierarchical labelling allowed us to present the results in more general terms to provide an overview and discuss specific spatial contextual factors in relation to specific ES and the mediating mechanisms related to this.

3. Results

3.1. Conceptual understanding of spatial context and mediating mechanisms in ES delivery

Review 1 showed that in the current ES literature, spatial context is represented by five general domains that together encompass both ecological and social structures and processes (Reyers et al., 2013). We labelled them as *aggregation of biophysical structures*, *natural structures and processes*, *built structures and processes*, *individuals and society* and *maintenance and governance* (see the upper section of Fig. 2). Spatial contextual factors related to *aggregation of biophysical structures* specify the case when the analysed biophysical structure is part of a larger service providing unit, i.e. when the characteristics of the unit or the configuration between the biophysical structures mediate the provided service (Andersson et al., 2015; Keeler et al., 2019). *Natural structures and processes* contain e.g. the position of the biophysical structure in the landscape, various environmental processes such as climate, flooding or air pollution at the location of the biophysical structure, as well as the relationship of the biophysical structure to other organisms (Andersson et al., 2015; Chiabai et al., 2018; Keeler et al., 2019). Spatial contextual factors labelled as *built structures and processes* include man-made infrastructure, land use, urban form or technological solutions, among others (Andersson et al., 2015; Keeler et al., 2019). The domain *individuals and society* contains for instance socio-economical, demographic or cultural context, as well as individually held values or perceptions (Andersson et al., 2015; Fedele et al., 2017; Keeler et al., 2019). Finally, rules, policies or maintenance influencing the biophysical structure are included in the *maintenance and governance* domain (Burkhard et al., 2014; Fedele et al., 2017; Fischer and Eastwood, 2016).

Integrating Review 1 in the framework of Fedele et al. (2017) resulted in a new interpretation of the mediating mechanisms (see the middle section of Fig. 2). In this interpretation, the first mechanism – *management* – can be understood as altering the functioning of the biophysical structure, thereby mediating its capacity (or potential) to provide ES. The name of the mechanism – *management* – might evoke mediation by humans such as protecting or establishing biophysical structures or their maintenance (Burkhard et al., 2014; Fischer and Eastwood, 2016), but in our interpretation, other structures and processes – topography, soils or spatial configuration (Andersson et al., 2015; Keeler et al., 2019) – can alter the functioning of the biophysical structure as well. The second mechanism – *mobilization* – mediates how much of the capacity is turned into a service. By service here we mean the final output of ecosystem function, still linked to the ecosystem. The allocation of this output to potential beneficiaries is mediated by the third mechanism – *allocation-appropriation*. Finally, the fourth mechanism – *appreciation* – mediates the demand for the output and thereby determines the value associated with it.

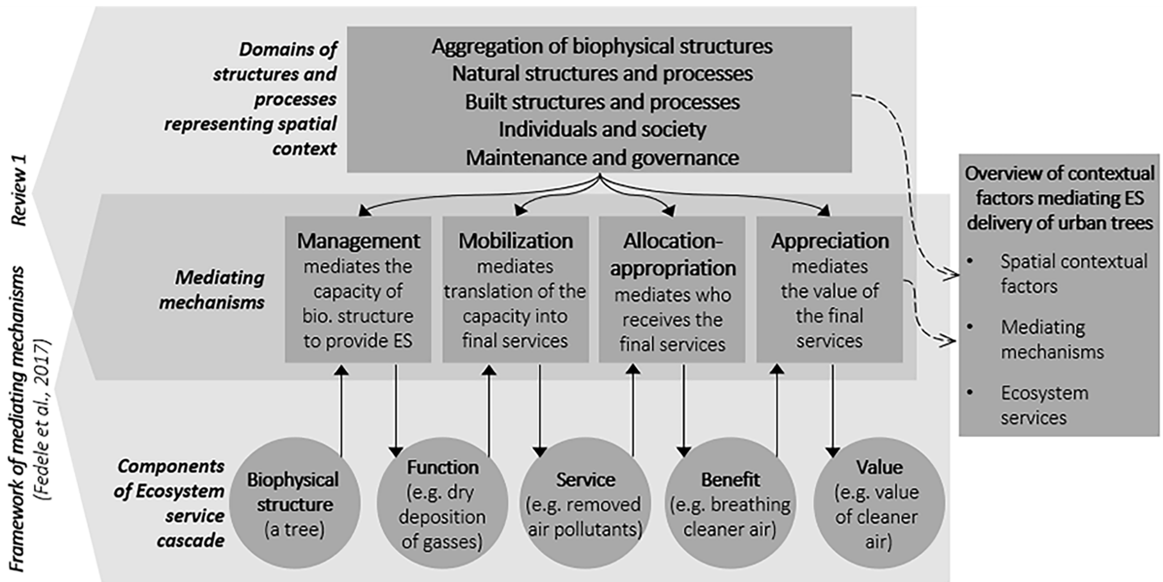

Fig. 2. Review 1 indicated that spatial context can be represented by five domains of structures and processes (upper section). Spatial context mediates ecosystem services by four mediating mechanisms (Fedele et al., 2017), newly interpreted using the findings of Review 1 (middle section). The solid arrows illustrate the linkage between spatial contextual factors, mediating mechanisms and components of the Ecosystem service cascade (bottom section). The dashed arrows illustrate how the results of Review 1 link to the overview of spatial contextual factors developed in this study.

3.2. Spatial contextual factors mediating ecosystem services of urban trees

In Review 2, we identified 861 notions of spatial contextual factors from 52 peer-reviewed journal articles that were categorised into 114 unique spatial contextual factors. These unique spatial contextual factors are organised into an overview that enables filtering the factors by mediated ES and provides information on the mediating mechanisms as well as underlying references. The resulting overview is provided in the Supplementary Material (sheet "Result"). Here, we present findings revealed by a synthesis of the overview.

3.2.1. Spatial contextual factors and the domains of structures and processes

The identified spatial contextual factors cover all five broad domains

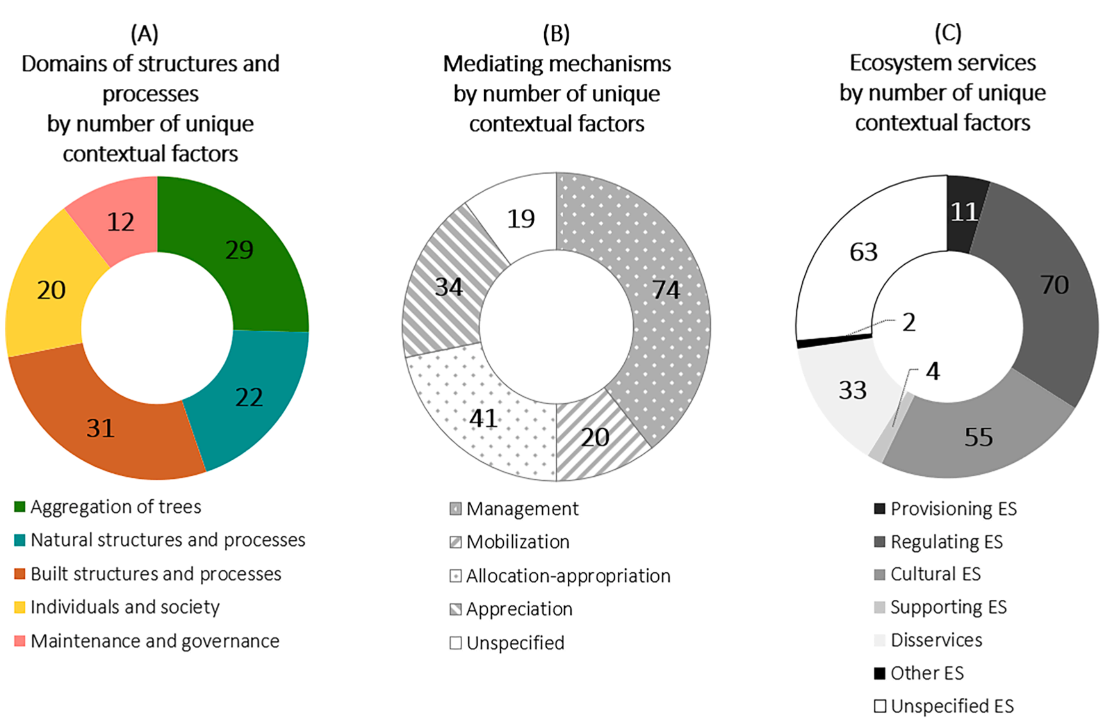

Fig. 3. Domains of structures and processes, mediating mechanisms and ecosystem services summarised by the number of spatial contextual factors within the respective category. In figure (B), category "unspecified" was used when the mediating mechanism of a spatial contextual factor was not explicitly described. In figure (C), category "unspecified" was used when a spatial contextual factor was mentioned without any link to a particular ecosystem service. Numbers of factors in figures (B) and (C) do not sum up to the total number of spatial contextual factors (114) because one factor might be related to more than one mediating mechanism or mediate more than one ecosystem service.

of structures and processes identified in Review 1. These are *aggregation of trees*, *natural structures and processes*, *built structures and processes*, *individuals and society* and *maintenance and governance*. Fig. 3A illustrates the number of spatial contextual factors found in each domain[4]. The largest number of spatial contextual factors is found in the domain *built structures and processes*, followed by *aggregation of trees*.

Spatial contextual factors from the domain *aggregation of trees* are descriptors of the structure and qualities of larger tree aggregates (such as parks, alleys or green corridors) that serve as service providing units. While many ES are delivered by single trees (e.g. air pollution removal), other ES can only be delivered if trees exist in larger aggregations (Andersson et al., 2015). For example, the potential of a tree to provide opportunities for outdoor recreation depends on the tree belonging to a larger green area, as well as on the size and shape of this area, its perceived qualities (safety, auditory environment) and its equipment or infrastructure (trails, benches, playgrounds) (Biernacka and Kronenberg, 2018; Bratman et al., 2019; Keeler et al., 2019).

The domain *natural structures and processes* contains spatial contextual factors related to characteristics of climatic and microclimatic conditions at tree location (e.g. temperature, wind conditions, precipitation), as well as characteristics of soils (e.g. chemical and physical characteristics, soil moisture), land cover (e.g. perviousness), terrain (e.g. site aspect) or water system (e.g. availability of water).

Within the domain *built structures and processes*, spatial contextual factors are related to buildings (e.g. building geometry and orientation), land use/building function (e.g. housing, hospital, but also private or public property), urban form (e.g. street canyon width, sky view factor), configuration of tree to building (e.g. visibility from building, direction to building) or configuration of tree to land use/building function (e.g. proximity or accessibility from housing, accessibility or visibility from hospitals). Included are also man-made environmental problems such as air pollution.

Included in the domain *individuals and society* are descriptors of socio-demographic and personal characteristics of individuals and society such as socio-economic status, cultural background, preferences and attitudes. Included are also spatial contextual factors related to the configuration of trees towards people, such as proximity, accessibility and visibility.

Finally, the domain *maintenance and governance* contains characteristics of maintenance (e.g. fertilization, pruning), institutional characteristics such as planning, policies and regulations and costs and values (e.g. pollutant costs, energy costs).

3.2.2. Mediating mechanisms

All four mediating mechanisms, as adopted from Fedele et al. (2017) and interpreted using the findings of Review 1, participate in the mediation of urban tree ES by the identified spatial contextual factors. In Fig. 3B, the individual mechanisms are compared in terms of the number of spatial contextual factors. *Management* is the most common way in which spatial contextual factors mediate ES, followed by *allocation-appropriation* and *appreciation*. *Mobilization* is the least common mechanism in which spatial contextual factors mediate ES and for 19 spatial contextual factors, the mediating mechanism is unspecified.

3.2.3. Relation between spatial contextual factors and ecosystem services

The identified spatial contextual factors are related to 31 unique ES, which cover the five main groups of ES – *provisioning*, *regulating*, *supporting* and *cultural services* and *ecosystem disservices*. In Fig. 3C, the groups of ES are compared in terms of the number of mediating spatial contextual factors. Most spatial contextual factors are related to regulating services, followed by cultural services. Many spatial contextual factors are also mentioned without any link to a particular ES. In many cases, these factors mediate tree growing conditions and might therefore be relevant for all ES (Jim et al., 2018; Steenberg et al., 2017; Vogt et al., 2017), but because specifications are not given, they are categorized as "unspecified".

The review further showed that some spatial contextual factors can mediate more than one ES. 69 spatial contextual factors mediate more than one ES and the median number of ES mediated by a spatial contextual factor is two. Species diversity is the single spatial contextual factor mediating the largest number of ES (11). ES mediated by species diversity include for instance outdoor temperature regulation (Jim and Chen, 2009), recreation and health (Bratman et al., 2019; Keeler et al., 2019), habitat provisioning (Roeland et al., 2019) and allergy disservice (Goodness et al., 2016).

Fig. 4 shows a ranking of spatial contextual factors on the second level of aggregation (i.e. grouped by the structures or processes in focus) based on the number of mediated ES. Configuration of tree to land use/building function from the domain *built structures and processes* mediates the highest number of ES (15); four groups of ES are mediated (provisioning, regulating and cultural ES and ecosystem disservices). There is no obvious pattern in the sense of a dominant domain that mediates more ES, but three of the five highest-ranked groups of spatial contextual factors exemplify the importance of people as a spatial contextual factor, either through their characteristics (i.e. socio-demographics) or through their spatial relationship with trees (i.e. configuration of tree to land use and building function, configuration of tree to people). Furthermore, three other highly ranked groups relate to the domain *aggregation of trees*, including its natural qualities, configuration and dimensions.

Besides ranking the spatial contextual factors using the number of ES they mediate, we can also investigate the dependency of individual ES on spatial contextual factors. Fig. 5 shows the 10 ES that are associated with the highest number of spatial contextual factors (a full list of ES is provided in sheet "ES" in the Supplementary Material). Recreation and health is mediated by the largest number of spatial contextual factors (53), mostly from the domain of *aggregation of trees* (e.g. its dimensions, perceived qualities or natural qualities mediating the suitability of the aggregation of trees for recreation) and *individuals and society* (e.g. personal characteristics and socio-demographics mediating the demand for/appreciation of the recreation service). This is followed by four regulating ES, all mediated by more than 15 spatial contextual factors, while the median number of spatial contextual factors mediating an ES is five.

3.2.4. Relation between domains of structures and processes, mediating mechanisms and ecosystem services

Fig. 6 summarises the resulting overview while making explicit the relationships between domains of structures and processes representing spatial context, mediating mechanisms and ES, which are illustrated as nodes in the graph. The width of edges between the nodes is proportional to the number of spatial contextual factors between the respective nodes. The colour of the edges corresponds to the colour of the respective domains. Reading the graph from the left side provides insight into which groups of ES the literature has identified as being mediated by a particular domain of structures and processes. For instance, spatial contextual factors from the domain *aggregation of trees* mediate all five groups of ES, but cultural ES are associated with the largest number of spatial contextual factors from this domain. On the other hand, *natural structures and processes* mediate only three groups of ES – regulating ES, cultural ES and ecosystem disservices. Starting from the right side of the graph, the figure also shows which domains of structures and processes the literature identifies as mediating a particular group of ES. For instance, cultural ES are predominantly mediated by the domain *aggregation of trees* and to a smaller extent by *natural structures and processes*, *built structures and processes* and by a few factors from the remaining domains. Supporting ES, on the other hand, are only

[4] Domains labelled as "unspecified" and "other" are not included in the figure. Factors included in these domains were not assigned with a common label and therefore cannot be counted.

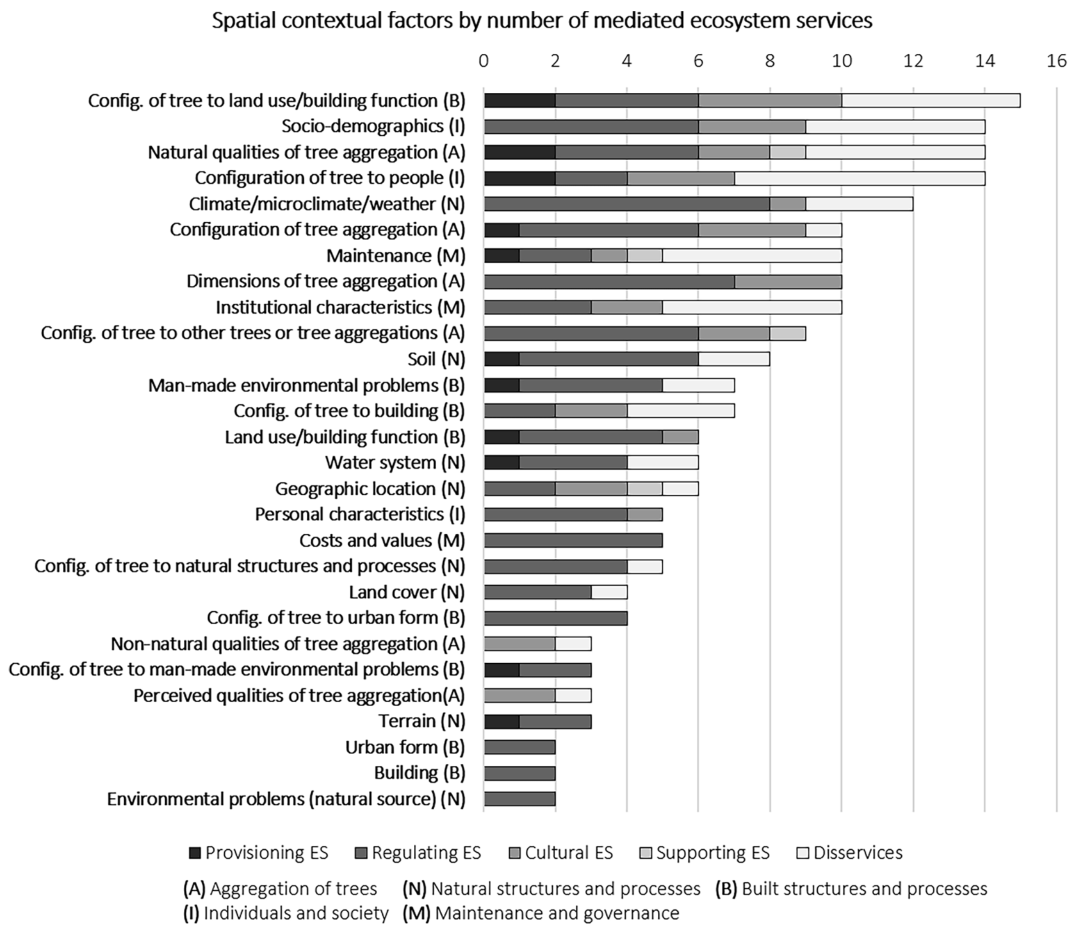

Fig. 4. Spatial contextual factors aggregated by similar structures and processes and ordered by the number of mediated ecosystem services. number of citations was used to determine the order in case of an equal number of mediated ecosystem services.

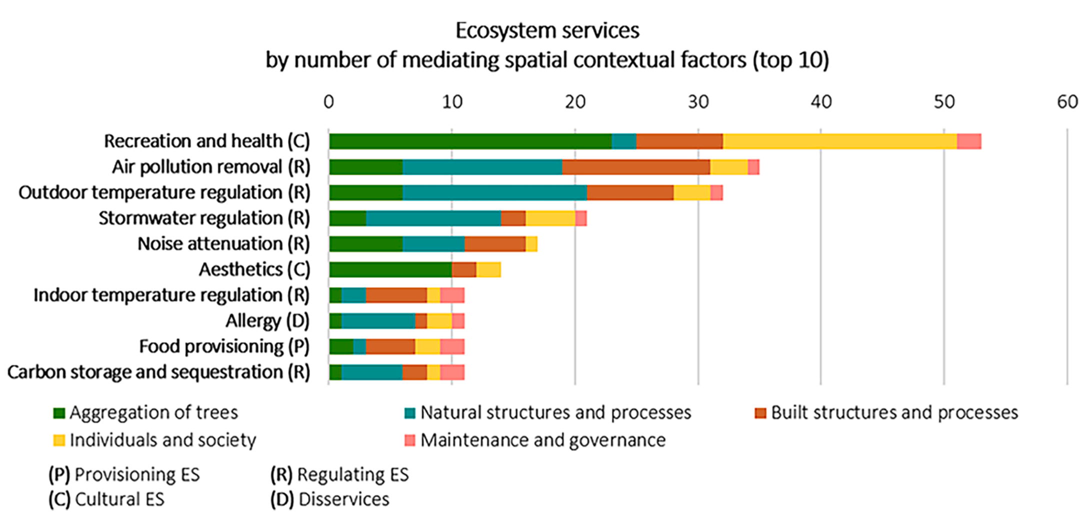

Fig. 5. Top 10 ecosystem services of urban trees ordered by the number of spatial contextual factors that mediate them. Unspecified services are not included in the diagram.

mediated by factors from the domain *aggregation of trees*. Finally, reading the graph from the perspective of mediating mechanisms makes it possible to see that *management* is the most common mechanism by which spatial contextual factors mediate all groups of ES of urban trees. The highest number of spatial contextual factors that mediate ES through *management* is within the domains *aggregation of trees* and *natural structures and processes*. *Built structures and processes* mostly mediate through *allocation-appropriation* and *management*, while for *individuals and society* and *maintenance and governance*, *appreciation* is the most common mediating mechanism. Only two spatial contextual factors mediate ES through *management* within the domain *individuals and society*, namely “proximity to people” and “knowledge”; because these two factors mediate two different services (fear and stress and carbon storage and sequestration, respectively), the width of respective edges between

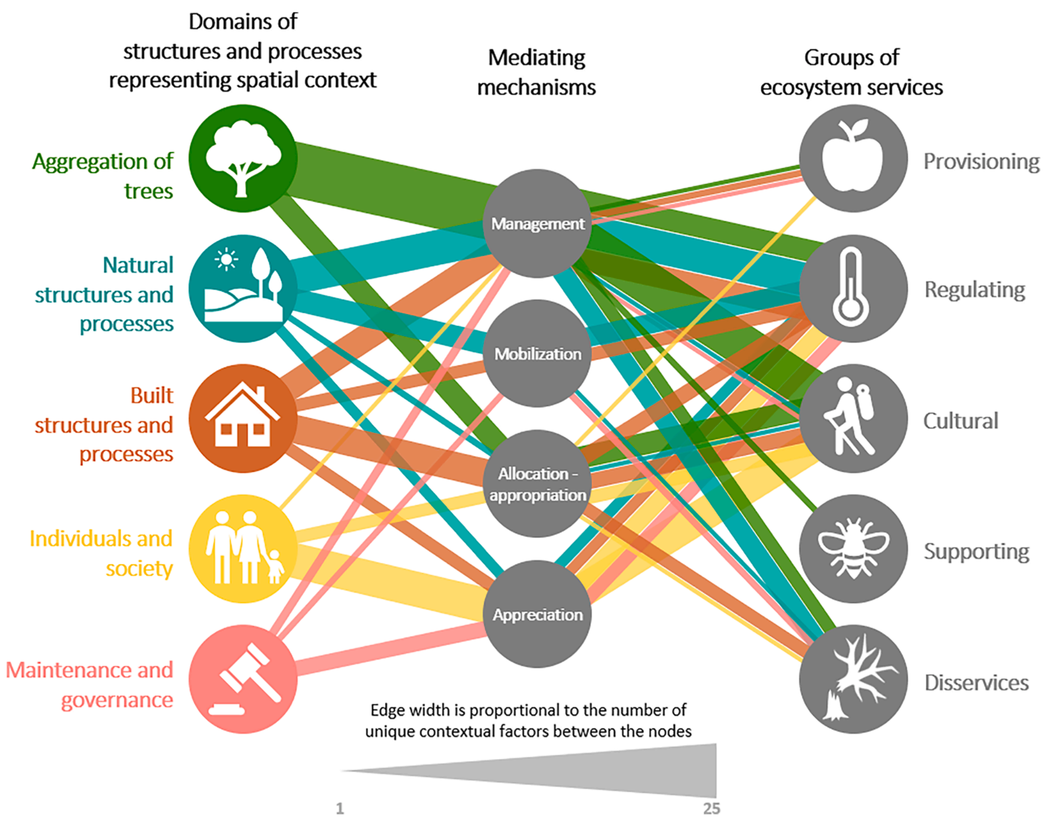

Fig. 6. Relationship between domains of structures and processes representing spatial context, mediating mechanisms and groups of ecosystem services (visualised as nodes). The width of edges between the nodes is proportional to the number of spatial contextual factors between the respective nodes. The colour of the edges corresponds to the colour of the respective domains. Edges containing only one spatial contextual factor (width equal to one) or related to other and unspecified factors, mechanisms or services are not shown.

mediating mechanisms and groups of ES is equal to one and therefore the edges are not shown.

4. Discussion

Our findings support other studies that emphasize the role of spatial context in the delivery of ES by urban trees and urban ecosystems (e.g. Andersson et al., 2015; Salmond et al., 2016; Wilkerson et al., 2018). Our findings complement these earlier studies by providing an overview of concrete spatial contextual factors that previously was missing and further linking the spatial contextual factors to specific ES of urban trees while keeping explicit the ways in which the factors mediate the ES (i.e. mediating mechanisms). The overview contains 114 unique spatial contextual factors related to 31 ES of urban trees and mediating through all four mechanisms introduced by Fedele et al. (2017).

Besides the overview, the results presented in this paper also help to draw more general conclusions on how tree location affects ES delivered by urban trees. For instance, species diversity is the single spatial contextual factor mediating the largest number of ES (11), which might be an important finding given the ongoing biodiversity loss in urban areas (Elmqvist et al., 2013). Most spatial contextual factors were found within the domain *built structures and processes*, which makes the understanding of where to plant trees an important question for architects and planners involved in urban development.

The review showed that *management* is the most common mechanism by which spatial contextual factors mediate all groups of ES of urban trees. In the ES cascade, this mechanism mediates the link between biophysical structure and ecosystem function, altering the functioning of the biophysical structure and thereby mediating its capacity to provide ES. All the consecutive components of the cascade, i.e. service, benefit and value, are therefore also affected by spatial contextual factors that mediate through *management*, which makes these spatial contextual factors particularly important for the delivery of ES by urban trees.

We have further shown that spatial contextual factors are often multifunctional in terms of the ES they mediate – one spatial contextual factor can affect many ES. These multifunctional factors could be described as the more important ones to include in tree planting strategies because they affect more than one ES and can thus represent an efficient use of resources. They are also potentially cost-effective points for measuring ecosystem condition for the purpose of urban ecosystem accounting (Keith et al., 2019; Wang et al., 2019). Our findings suggest that people are highly multifunctional spatial contextual factors, directly through their physical location or socio-demographic profile and indirectly through different land uses or building functions. This finding, in turn, highlights the significance of whom the user of the service is, such as specific groups in society or specific building functions. This highlights again the importance of planning and design in tree planting strategies.

Our results can be used to give insight into the dependency of individual ES on spatial contextual factor, where ES mediated by many spatial contextual factors can be interpreted as highly dependent on design and planning. The number shows a large variation. The most spatial context-dependent ES of urban trees is recreation and health, followed by various regulating services such as air pollution removal and outdoor temperature regulation. Without having direct evidence, a hypothesis further derived from these results is that this highlights the need for integrative planning approaches, because of the risk that such highly mediated and spatial context-dependent ES are more easily neglected in sectorized or ‘siloed’ urban planning processes. It also highlights a need for tools to measure the complex impact of spatial context on tree performance.

4.1. *Relevance for urban planning and tree planting strategies*

Besides the better understanding of how tree location affects ES delivered by urban trees as discussed above, the information in the resulting overview is aggregated at a level we believe could be useful for providing planning practice with knowledge to develop tree planting strategies that better support the delivery of ES. For instance, planting strategies can become more effective in delivering ES through a better understanding of where trees are most needed or where tree planting should be avoided because the spatial context endangers tree survival or substantially increases management costs. The overview developed in this paper can support planting strategies by allowing planners and other professionals and researchers to query the overview in different ways. For example, the results can help to answer a question such as “which spatial contextual factors need to be taken into account when planting trees for a particular ES?”. For example, to support air pollution removal, there are 29 spatial contextual factors to be considered, sorted by the domain of structures and processes (Table 1).

Table 1
Spatial contextual factors mediating air pollution removal by urban trees, obtained by querying the resulting overview and sorted by the domain of structures and processes.

Domains of structures and processes	Spatial contextual factors	Mediating mechanisms
Aggregation of trees	Height of tree aggregation	Management
	Width of tree aggregation	Management
	Species diversity	Management
	Density of tree aggregation	Management
	Connectivity to other trees/ aggregations of trees	Management
	Proximity to other trees/ aggregations of trees	Management
Natural structures and processes	Climate	Management
	Humidity	Management, Mobilization
	Light conditions	Management
	Precipitation	Management
	Temperature	Management, Mobilization
	Ventilation	Management
	Weather	Management
	Wind direction	Management, Mobilization, Unspecified
	Wind speed	Management, Mobilization, Unspecified
	Proportion of canopy cover to other land covers	Management
	Soil moisture	Management
	Water availability	Management
	Proximity to coast	Appreciation
Built structures and processes	Traffic density	Mobilization
	Proximity or accessibility from housing	Allocation-appropriation
	Proximity or visibility from hospitals	Allocation-appropriation
	Proximity to green areas	Allocation-appropriation
	Proximity to infrastructure	Appreciation, Management, Mobilization
	Proximity to parking locations	Allocation-appropriation
	Air quality	Management, Mobilization
	Proximity to air pollution source	Mobilization
	Street canyon aspect ratio	Management
	Street canyon width	Management
	Urban form type	Management
	Position in street canyon	Management
Individuals and society	Behaviour	Appreciation
	Health	Appreciation
	Age	Appreciation
Maintenance and governance	Pollutant costs	Appreciation

The overview can also be used to understand how a specific spatial contextual factor affects ES delivery by urban trees, i.e. it can help to answer the question “which ES provided by a particular tree would be altered by changes in the surrounding structures and processes?”. For example, “area of tree aggregation” mediates six different ES including regulating and cultural services and changing the area of tree aggregation will affect carbon storage, outdoor temperature and wind regulation, aesthetics, recreation and health, and social cohesion (Table 2). Further, “visibility from building” mediates two cultural services, and “socio-economic status” mediates 10 different ES including regulating and cultural services and ecosystem disservices.

The range of applications based on the overview presented in this paper is potentially much wider. Apart from scoping strategic tree planting, the overview could serve as a checklist in urban open space design processes (Jansson and Randrup, 2020). Furthermore, the overview provides useful information for generalizing valuation studies to entire urban accounting areas, where some form of benefit transfer is required (Johnston et al., 2020). Benefit transfer assumes that the contextual factors are constant, or possible to control for, between the reference and transfer site and that there are value function and meta-analytic transfer methods to deal with known differences. The overview presented in this study provides a systematic list of contextual factors that need to be considered to minimize the risks for over- or underestimations with benefit transfers.

Table 2
Ecosystem services mediated by spatial contextual factors “area of tree aggregation”, “visibility from building” and “socio-economic status”, obtained by querying the resulting overview.

Spatial contextual factors	Ecosystem services		Mediating mechanisms
Area of tree aggregation	Regulating services	Carbon storage and sequestration	Management
	Regulating services	Outdoor temperature regulation	Management
	Regulating services	Wind regulation	Management
	Cultural services	Aesthetics	Management
	Cultural services	Recreation and health	Allocation-appropriation, Management
	Cultural services	Social cohesion	Management
Visibility from building	Cultural services	Aesthetics	Allocation-appropriation
	Cultural services	Recreation and health	Allocation-appropriation
Socio-economic status	Regulating services	Outdoor temperature regulation	Appreciation, Unspecified
	Regulating services	Stormwater regulation	Appreciation
	Regulating services	Water supply	Appreciation
	Cultural services	Education	Appreciation
	Cultural services	Recreation and health	Appreciation
	Disservices	Allergy	Appreciation
	Disservices	Damages to infrastructure	Appreciation
	Disservices	Decrease in air quality (ozone and PM formation)	Appreciation
	Disservices	Fruit and leaf fall	Appreciation
	Disservices	Maintenance emissions	Appreciation

4.2. Limitations and future research

The overview of spatial contextual factors revealed by the review and its synthesis presented here does not claim to cover the full range of spatial contextual factors mediating ES of urban trees. First, the review did not include grey literature such as research reports, design guidelines or policy reports. This might have influenced the results towards dominance of factors where data are available, while design guidelines or policy reports might have been more focused on factors that can be influenced through design. Second, due to a so-called "street light effect", spatial contextual factors that are more often discussed in the scientific literature might be overrepresented, while spatial contextual factors that are less studied might not have been revealed. It should therefore be noted that if a particular link between ES, mediating mechanism and spatial contextual factor was not uncovered, it does not mean that such a link does not exist or is not important, but rather that it was not addressed in the literature. Moreover, when identifying spatial contextual factors, we intended to distinguish between all small nuances available from the reviewed articles. In consequence, ES of urban trees studied in larger detail are likely to reveal larger numbers of more detailed spatial contextual factors. For instance, we found a great number of spatial contextual factors related to regulating ES and only a small number of factors related to supporting ES. However, this does not necessarily mean that supporting ES are less context-dependent, but rather that the current research focuses more on regulating ES of urban trees.

Furthermore, the results are also affected by the categorization choices made when aggregating spatial contextual factors. This is a general issue relevant to any categorization task. We acknowledge that some spatial contextual factors may be categorised differently or placed in between two categories. For instance, we placed the factor "air quality" in the domain *built structures and processes*, because it can be considered a consequence of human activity. However, one might argue that this factor can also be placed in the domain *natural structures and processes*. Similarly, associating some spatial contextual factors with mediating mechanisms was not always straightforward. For example, various environmental problems such as air pollution can be interpreted as either *mobilization* (i.e. mediating how much of the capacity to provide an ES is turned into an actual service) or *appreciation* (i.e. mediating the demand for the ES). To be transparent about our choices and allow for future modifications based on new insights, we, therefore, provide all data used in the process of our categorization choices in the Supplementary Material.

For the aggregate presentation of the resulting overview of spatial contextual factors, we have summarized the spatial contextual factors by the number of ES they mediate and domains of structures and processes, ecosystem services and mediating mechanisms by the number of spatial contextual factors. However, caution must be paid when drawing conclusions from these relative frequencies, as they do not aim to express the relative importance of individual spatial contextual factors. This information can be found by searching the individual articles, but a meta-analysis quantifying the effect of individual spatial contextual factors in ES delivery by urban trees would be an important next step for developing the understanding of ES of urban trees.

Future research could also investigate how spatial contextual factors are currently addressed in urban planning practices to assess the ease of implementing the different factors in planning, as well as explore how to make practitioners in different sector agencies more aware of factors that are currently not addressed. Another direction for future research considers the quantification and modelling of spatial contextual factors to make ES assessments of existing urban environments and evaluate design proposals. For example, quantifying spatial contextual factors can provide empirical evidence for planning practice in assessing various tree planting strategies. Furthermore, quantification of tree characteristics, including spatial contextual factors, is in many cases the foundation for tree valuation based on the delivered ES using tools such as i-Tree Eco or VAT03 ("i-Tree Eco v.6," n.d.; Randrup et al., 2018). Cost-effective ecosystem condition accounting could further be improved by including actual mediators of ES, rather than ad hoc compilation of available environmental monitoring data. Therefore, future work should also investigate methods for quantification and modelling spatial contextual factors.

The resulting overview presents spatial contextual factors – however, the spatiality of the individual factors varies. For example, the factors "management practices" or "personal characteristics" are not explicitly spatial but can be understood as occurring in space and vary across different locations. On the other hand, the factor "visibility of tree to people" is a clear example of high spatiality. We believe that this distinction can be useful for addressing the spatial context of urban trees in urban planning practice. For example, the largest number of spatial contextual factors explicitly mentioning the spatial relationship between a tree and a structure or process was found within the domain *built structures and processes*, which highlights the complexity of the design question at hand – it is not only the presence of buildings or transport which is relevant for the delivery of ES by urban trees but also the proximity or visibility of them. Thinking of the spatial component of the identified factors on a gradient between absolute and relative space (Harvey, 2004) might be useful for this purpose. Similar variability can be found in the spatial and temporal resolutions and scales of the identified spatial contextual factors. For example, while climate describes the global spatial context, weather describes a more local spatial context; in a similar manner, climate and weather describe two very different temporal scales. We consider these ways of thinking worth further exploration. In addition, we also see a potential for further research in the development of advanced spatial analysis methods that will enable to quantitatively assess and model these highly-spatial or large-scale contextual factors.

Given the relatively small number of articles identified in Review 1 (8), there is uncertainty in the proposed categorisation of domains of structures and processes representing spatial context and in the interpretation of mediating mechanisms. In consequence, the result of Review 1 should not be interpreted as the final defined set of categories and relations. Instead, it should be understood as a proposal for organising the links between ES, mediating mechanisms and spatial contextual factors. Further research is needed to establish a more solid conceptual understanding of spatial context in the ES delivery process. In this paper, we have chosen to build our conceptual understanding of spatial context around the ES cascade framework developed by Haines-Young and Potschin (2010) and Fedele et al. (2017), but other conceptual frameworks could possibly have been used instead (for an overview of various ES frameworks, see e.g. Fisher et al. (2013)). However, the choice of a framework was not at the core of this study and merely used to reach the main objective of this paper. To build a solid conceptual understanding of spatial context in ES delivery, future research should explore and discuss the effect of the various ES frameworks. The insight developed in this study can be used as a starting point.

5. Conclusions

The influence of spatial context on the delivery of ES has been highlighted before (e.g. Andersson et al., 2015; Wilkerson et al., 2018; Bruckmeier, 2016). In this paper, we have developed a systematic overview of spatial contextual factors that are currently recognised by research as being relevant for the delivery of ES by urban trees, in order to support tree planting strategies effective at the delivery of ES.

Our findings point out the importance of design and planning in supporting ES delivery by urban trees. First, of all spatial contextual factors, people are found to mediate the highest number of ES of urban trees. Second, the highest number of spatial contextual factors was found within the domain *built structures and processes.*

The overview developed here enables researchers as well as urban planners and tree managers to identify the spatial contextual factors that are of importance to a particular ES and see which ES are mediated by a particular spatial contextual factor. This, in turn, will provide the knowledge needed to ensure, support and maintain ES of urban trees and bring more insight into developing tree planting strategies that are more effective in providing ES.

The overview might further benefit other practical applications such as environmental benefit transfer (Johnston et al., 2020) or ecosystem condition accounts (Keith et al., 2019; Wang et al., 2019) in the context of experimental ecosystem accounting. A meta-analysis of the importance of individual spatial contextual factors in terms of their impact on ES delivery remains to be addressed by future research.

Finally, by uncovering which structures and processes represent the spatial context in general and then associating the role of spatial context, through mediating mechanisms, with the ES cascade, we have also contributed to a better conceptual understanding of what spatial context is in relation to ES delivery in general.

CRediT authorship contribution statement

Zofie Cimburova: Conceptualization, Methodology, Formal analysis, Writing - original draft, Writing - review & editing, Visualization. **Meta Berghauser Pont:** Conceptualization, Writing - original draft, Writing - review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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